Understanding Winter Windstorm Predictability over Europe

Lisa Degenhardt[1], Gregor C Leckebusch[1,2], and Adam A Scaife[3,4]

[1]Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK
[2]Institute for Meteorologie, Freie Universitäte Berlin, Berlin, Germany
[3]Hadley Centre for Climate Prediction and Research, Met Office, Exeter, UK
[4]Faculty of Environment, Science and Economy, University of Exeter, Exeter, UK

Correspondence: Lisa Degenhardt (LXD943@student.bham.ac.uk)

Abstract. Winter windstorms are one of the most damaging meteorological events in the extra-tropics. Their impact on society makes it essential to understand and improve the seasonal ~~forecast~~ forecasts of these extreme events. Skilful predictions on a seasonal time scale have been shown in previous studies by investigating hindcasts from various forecast centres. This study aims to connect forecast skill to relevant dynamical factors. Therefore, ~~10~~ a number of factors have been selected which are known to influence either windstorms directly or their synoptic relevant systems, cyclones. These factors are tested with a re-analysis (ERA5~~and GloSea5 seasonal hindcasts~~) and the seasonal hindcast of the UK Met Office (GloSea5) for their relation to windstorm forecast performance.

~~Following~~ GloSea5 factors' ~~validation contributing~~ are (1) validated on the physical connections to windstorms, (2) investigated on the seasonal forecast skill of the factors themselves~~and~~, and (3) assessed on the relevance and influence of their forecast ~~quality~~ performance to windstorm forecast~~quality is assessed~~. Factors like mean-sea-level pressure gradient, sea surface temperature, equivalent potential temperature and Eady Growth Rate show ~~coherent~~ consistent results within these three steps~~,~~ ~~meaning these~~. Their physical connection is therefore assumed to be well represented in the model. These factors are skilfully predicted in ~~relevant regionsleading~~ storm-relevant regions. And this skill leads to increased forecast skill of winter windstorms over Europe. Nevertheless, not all factors show this clear ~~signal of~~ process chain for a forecast skill improvement for winter windstorms, and this might indicate potential for further model improvements or ~~further~~ understanding to improve seasonal winter windstorm predictions.

1 Introduction

Severe winter windstorms are one of the most damaging and loss-bringing events in the extra-tropics, especially for the European region (MunichRE, 2010). Hence, it is of great scientific interest ~~as well as~~ for stakeholders and the general public to understand these ~~rare~~ extreme events. Studies use various algorithms to identify and track cyclones (Neu et al., 2013). This study aims at understanding an even more extreme event, the surface-near windstorm, which is produced by the strongest of extra-tropical cyclones. Windstorms in this study are thus more related to the direct impacts of a cyclonic system rather than just the low-pressure systems. Leckebusch et al. (2008) developed an objective tracking algorithm for these strongest wind events. They used a threshold that intentionally relates to observed losses (Klawa and Ulbrich, 2003) and detects about the top 2% strongest, coherent extreme events in the extra-tropics. This objective windstorm tracking has been used for multiple different studies in the past, spanning ~~from~~ different regions and hazards (Ng and Leckebusch, 2021; Nissen et al., 2013), individual event analysis (Donat et al., 2011b) over climate (Donat et al., 2011a; Schuster et al., 2019) and seasonal studies (Befort et al., 2019; Renggli et al., 2011; Walz et al., 2018a; Degenhardt et al., 2022).

Seasonal hindcasts have been investigated in multiple studies for different ~~storm relevant~~ storm-relevant aspects, like the forecast skill of the North Atlantic Oscillation (NAO; Parker et al., 2019; Athanasiadis et al., 2017; Scaife et al., 2019, 2014), stratospheric conditions (Nie et al., 2019b) or connections between tropical cyclones and extra-tropical storms (Angus and Leckebusch, 2020). In addition, different regions and events were investigated ~~with respect to~~ concerning their seasonal forecast skill (Dunstone et al., 2018; Scaife et al., 2017a). For extreme European winter windstorms, one of the first studies was published in Renggli et al. (2011) based on DEMETER (Palmer et al., 2004) and ENSEMBLES (Weisheimer et al., 2009) pilot seasonal hindcasts. More recent studies investigated later operational systems, like the ECMWF systems (SEAS 3 and 4) and the UK Met Office's GloSea5 (Global Seasonal forecasting system version 5) (Befort et al., 2019). They found forecast skill in windstorm frequencies and their relation to the large-scale pattern of the NAO. Following ~~on from~~ this, Degenhardt et al. (2022) found a strong positive and significant ~~signal~~ forecast skill for windstorm frequency and (for the first time) intensity. A connection to the three dominant ~~large-scales~~ large-scale patterns over Europe showed the NAO, Scandinavian Pattern and East-Atlantic Pattern together explain between 60% and 80% of interannual variability of windstorms over Europe in this seasonal hindcasts, corroborating results from Walz et al. (2018a) based on century-long reanalysis data. ~~This leads~~ These skilful storm forecasts found in seasonal hindcasts lead to the motivation for this study~~,~~. This study aims to understand which ~~factors are driving~~ dynamical factors drive the seasonal winter windstorm prediction skill~~, whether as primary or secondary related factors~~.

Multiple studies have investigated dynamical factors influencing cyclone and storm generation and intensification in the past. The Eady Growth Rate (EGR) parameter (Eady, 1949) is used as a standard measure for baroclinic instability of the atmospheric flow ~~and~~ which is known as a source and intensifying factor for extra-tropical cyclones (Hoskins and Valdes, 1990). Later, ~~i.a~~e.g. Pinto et al. (2008) investigated important dynamical factors and their connection to strong cyclones over Europe for future climate change scenarios, based on previously identified contributors like EGR in the upper troposphere (Hoskins and Hodges, 2002), upper-troposphere divergence (Ulbrich et al., 2001), the jet stream speed (Kurz, 1990; Hoskins et al., 1983; Shaw et al., 2016) and the equivalent-potential temperature ~~(Θ_e; Chang et al., 1984). These variables were also used in other studies (Pinto et al., 2008; Hansen et al., 2019; Walz et al., 2018b; Priestley et al., 2023)~~(Θ_e), as another stability measure (Chang et al., 1984).

For EGR, this study uses the same diagnostic level of 400hPa as in Pinto et al. (2008) for the upper troposphere ~~but also~~ and 700hPa (resulting from 2 available model levels) to diagnose lower troposphere baroclinicity. The location and strength of the jet stream ~~is~~ are important for whether the end of the North Atlantic storm track reaches Europe (Parker et al., 2019). Θ_e is a parameter that describes the temperature of a fully dried air parcel dry-adiabatically lowered onto a reference level, usually 1000hPa (Bolton, 1980). It is not only a measurement ~~for~~ of the moisture content in the atmosphere and its static stability but links to the concept of the isentropic Potential Vorticity ~~(PV; i.a. Hoskins, 2015; Hoskins et al., 1985)~~ (PV; e.g. Hoskins, 2015; Hoskins et al., 1985). Thus, Raymond (1992) could demonstrate that latent heat release leads to a redistribution of PV, with positive PV tendencies below the ~~level of maximum heating~~ maximum heating level and negative tendencies above. It is known that the downwards propagation of upper tropospheric positive PV anomaly favours the strengthening of cyclones (Hoskins et al., 1985; Büeler and Pfahl, 2017). Hence, ~~it~~ PV is connected to cyclonic systems and can ~~be an indicator for~~ indicate their strength and location over the North Atlantic. Hoskins et al. (1985) compared different isentropic levels for the PV, including 350K, which is used in this study as it is a good average representative for the synoptic scales in the troposphere. They have also connected this concept with the Rossby Wave transition. Upper-troposphere Divergence is also part of the equation for the Rossby Wave Source (RWS), a measure of developing Rossby waves which are transporting cyclones and potentially transporting predictability from the tropics to the extra-tropics (Beverley et al., 2019; Dunstone et al., 2018; Scaife et al., 2017b).

Other influencing factors for the generation and intensification of cyclones ~~,~~ are the general environmental conditions which are thus indirectly connected to windstorms like the sea surface temperature (SST) distribution, SST Gradient and mean sea level pressure (MSLP) gradient (Shaw et al., 2016). ~~These contributing environmental factors will be called secondary factors in the following, while factors like EGR or PV which have a direct influence on cyclones and windstorms are called primary factors.~~ Recently, the SST and the jet stream have been identified as drivers for storm track biases in CMIP6 data (Priestley et al., 2023). Beyond those generally ~~well established~~ well-established factors, other studies identify the important role of tropical precipitation as an indicator for European climate predictability (e.g. Scaife et al., 2017b): tropical convective precipitation triggers enhanced vertical lifting, which again leads to the establishment of Rossby Waves trains ~~impacting~~ to impact on Europe. ~~Further on, Wild et al. (2015) discovered~~ Another factor discovered by Wild et al. (2015), investigates a dependency of the windstorm frequency over Europe on the temperature gradient between North American surface temperature anomalies and those of the SST over the western North Atlantic.

This study investigates ~~primary and secondary~~ dynamical factors connected to windstorms in seasonal forecasts from the UK Met Office, GloSea5 (MacLachlan et al., 2015), and the respective seasonal windstorm forecast skill. This ~~could lead to better knowledge~~ study aims for a better understanding of the origin of the seasonal forecast skill and hence confidence in ~~real time~~ real-time forecasts.

This study uses a 3-step approach to understand the role of different ~~primary and secondary~~ dynamical factors for the winter windstorm predictability over Europe.

Step 1: Validation of dynamical factors: Is the observed physical link between factor and storm well represented in the model?

Step 2: Skill of Factors: Is the dynamical factor ~~itself skilfully predicted~~ skilfully predicted on a seasonal scale?

Step 3: Relevance of Factors for Storm forecast skill: Is the forecast skill of windstorms related to the factor’s forecast skill ~~or factor-related “~~in general, or related to specific ”centres of activity~~”~~”, i.e. is it more important to have skill in those specific regions which are closest linked to wind-storm generation?

The study will first introduce the data sets used in section 2, followed by a description of applied methods in section 3. In section 4, the results are presented ~~,~~ and structured within the ~~above mentioned 3-step-approach~~above-mentioned 3-step approach. The study finishes with a discussion and conclusion presented in ~~chapter~~ section 5.

2 Data

This study investigates the seasonal forecast ~~model~~ of the UK Met Office’s Global Seasonal Forecasting System version 5 (GloSea5; MacLachlan et al., 2015), in comparison to ECMWF re-analysis, ERA5 (Hersbach et al., 2019). Both data sets are used for ~~the~~ a consistent time from 1993 to 2016. GloSea5 is a multi-member ensemble model with 4 initialisations per ~~months~~ month (on the 1^{st}, 9^{th}, 17^{th} & 25^{th} of each month) and 7 members per initialisation. Currently, 3 different model versions are available~~which just~~ , which differ in small system updates. This study investigates the northern hemisphere winter (December to February, DJF) and therefore uses initialisation around the 1st of November (25^{th} Oct., 1^{st} and 9^{th} Nov.). This leads to 63 ensemble members for GloSea5 (3 system updates x 7 members x 3 initialisations)~~used here for GloSea5~~. The seasonal model output has a spatial resolution of 0.83° longitude x 0.56° latitude. ERA5 is a commonly used re-analysis and provides observation-near data, which are used as a reference in this study. The reference data set has a resolution of 0.25x0.25°. Further details of ERA5 can be found in Hersbach et al. (2019). All factors are calculated as described in the method section ~~and~~ (including the appendix), and the used variables and levels ~~used are presented~~ are summarised in Tab. 1 (for the focused factors and Tab. A1 in the Appendix for all factors). The windstorm tracking is based on 10m wind speeds for the calculation (details cf. below). In the case of a grid-cell by grid-cell comparison of both data sets, a re-gridding from ERA5 to the spatial resolution of GloSea5 has been done by a bilinear interpolation using Climate Data Operators (Schulzweida, 2019).

~~Scheme of dynamical factor connection to cyclones and windstorms.~~

~~Schematic map of location of factors in comparison to an idealised storm system.~~

3 Method

3.1 Storm Tracking

The windstorm analysis is done via an ~~impact based algorithm ,~~ impact-based algorithm developed by Leckebusch et al. (2008). This objective identification and tracking uses a clustered exceedance of the 98^{th} percentile of surface wind speeds. These synoptic-scale wind clusters are tracked following a ~~nearest neighbour~~ nearest-neighbour approach. Only events above a minimum size and duration will be considered: a coherent wind cluster must persist for at least 48 hours and reach at least a size of 130.000 km^2 (cf. details e.g., in Leckebusch et al., 2008). Consequently, an individual storm track and a grid cell-based footprint of each storm is created. This footprint is used to count the number of storms over a defined region. The target area in

Table 1. Dynamical Factors (focused in ~~connection to~~ this paper) concerning storminess, cyclones or windstorms over Europe.

Factor	Version	Level	Parameter (ERA5/GloSea5)	Analysis Regions
~~Temperature Dipole index North America (105°-80° W, 38°-55° N) North Atlantic (85°-50° W, 15°-35° N)~~ Sea-Surface Temperature	Original	Surface	sea surface temperature (6h/6h)	~~Gradient meridional Gradient Gradient~~ Boxes of 10°x10° over North Atlantic
Mean Sea-Level Pressure	~~Meridional~~ Gradient		mean sea level pressure (6h/6h)	
~~mean Only December mean Location Speed original Bandpass 2-8d Advection 400hPa~~				
Equivalent potential Temperature Θ_e		850hPa	u- & v-wind component, temperature T (6h/12h)	
~~original 3d variability Bandpass 2-4d~~				
Eady Growth Rate	original	~~700hPa Divergence Rossby Wave Source~~ 400hPa	u, T, Geopotential (6h/12h)	

this study ~~in~~ is the extended area of the British Isles (-15° to 10° E & 48° to 60° N). Recently, the authors showed significantly skilful seasonal windstorm predictions for this area (Degenhardt et al., 2022). The individual windstorm tracks are also used to calculate the track density (used in section 4.3; Kruschke, 2015).

3.2 Factors

Dynamical factors are selected by previously known connections to windstorms or cyclones. ~~The selected factors can be separated into primary and secondary dynamical factors in regard to their connection to windstorms. Hence, primary factors,~~ Factors like EGR or PV, are dynamical factors which act on a smaller and shorter scale but can influence the cyclone or windstorm directly~~/primarily. Secondary~~. Other factors are acting on a larger and longer scale. These are, for example, MSLP gradient or SST, and they have a more indirect ~~/secondary~~ link to windstorms as they reflect the general state of atmospheric conditions. A summary of all factors and the way they are used can be found in Table ~~1~~A1. Individual factors are used as seasonal (~~3 month~~3-month) averages in the following analysis.

More details about the different ways of calculating the factors can be found in the appendix. The standard calculations have been used, e.g., the gradient of MSLP and SST, the jet characteristics (Parker et al., 2019), or the divergence in 200hPa. Other factors ~~has been calculated followed~~ have been calculated following original studies, like EGR ~~Eady (1949)~~(Eady, 1949), or PV ~~Hoskins et al. (1985)~~(Hoskins et al., 1985). More unique factors like Rossby Wave Source (RWS) have been calculated as described in~~i.a~~, e.g. Beverley et al. (2019) or the Temperature Dipole used from Wild et al. (2015).

~~A schematic highlighting the different connections and interactions, is presented in Fig. 1 and 2, illustrating the physical connectivity between different factors to each other and to cyclones and windstorms in general. The coloured boxes indicate in which physical view (Quasi-geostrophic Omega- and PV-theory) these factors are included. Fig. 2 is a more exemplary scheme~~ Fig. A1 in the Appendix is an exemplary schematic of an idealised storm-cyclone system, highlighting where the respective factors would be expected to be ~~important. EGR~~ of relevance. EGR (green), as one of the most important factors to strengthen cyclones, is located ~~north-east~~ northeast of the storm centre (at the lowest level) and ~~has a slope towards northwest with increasing~~ slopes towards the northwest with decreasing pressure levels. The upper tropospheric baroclinicity (EGR 400hPa) triggers respective upper-level divergence (peach) and hence, creates the jet stream (orange). The counterpart to this is the SST (ocean colour) which influences the ~~low level~~ low-level baroclinicity (EGR 700hPa), which impacts ~~on~~ the MSLP gradient ~~. The relation of~~ (light blue) and hence, the wind speed (yellow). Another process related to the potential predictability of windstorms ~~to~~ is caused by convective tropical precipitation (dark blue) via vertical lifting, triggering a Rossby wave train ~~formation over~~ (purple) formation to the North Atlantic region in higher ~~pressure levels) is tested~~altitudes.

3.3 Composite Analysis

To understand how and when those factors ~~are influencing~~ and the windstorm forecast quality influence each other, a composite analysis has been done by separating data sets into two different anomaly categories depending on storm frequency and factor prediction skill, respectively.

Firstly, ~~a~~ separation is done by the number of storms, thus the seasons' overall activity (used in Fig. 1). The storm counts over the extended area of the British Isles (-15° to 10° E & 48° to 60° N) in ERA5, and each GloSea5 ensemble ~~member~~ members are used and separated into 3 categories, the 10 strongest seasons, the 10 weakest seasons and the 3 neutral seasons (10-3-10). A separation into 10-3-10-splitting has the aim of still using data sets with at least ~~a decade long duration~~ 10 years of data to achieve representative results ~~,~~ but also to ignore the 3 neutral seasons to reduce the noise. The separation is done individually per model ensemble member to ensure that each composite compares strong vs weak storm seasons internally. This might lead to different seasons within the sub-samples. The strong-weak-composites are presented as (member-individual) standardised composite anomalies ~~,~~ to allow for a clear comparison between the ERA5 and GloSea5 data sets. An example categorisation for individual years can be seen in the appendix (Fig. A2) for ERA5 and GloSea5 ensemble mean windstorm counts in the UK region.

~~Secondly, a categorisation with respect to~~ The second categorisation (used in Fig. 4) uses the forecast skill ~~is used~~of the respective factor: well (~~bad~~badly) forecasted years are identified ~~by~~ using the absolute difference of ~~seasonal storm counts~~ the respective seasonally averaged factor over an individually defined region in the GloSea5 ~~and ERA~~ensemble mean and ERA5. These categories are built for consistency ~~as well~~ according to the 10-3-10 approach again, i.e., the 10 seasons with the lowest (greatest) absolute difference are used as ~~well (bad~~well- (badly-) predicted seasons. ~~An example categorisation for individual years can be seen in the appendix (Fig. A1), for ERA5 and GloSea5 ensemble mean windstorm counts in the UK region.~~ Both composite methods are presented as composite ~~anomalies differences, which are~~ anomaly differences, tested for significance via a student's t-Test.

3.4 Statistical metric of prediction skill

All ~~steps of the approach~~ approach steps include correlations, here performed using ranked τ_b-Kendall correlations (Kendall, 1945) . Kendall correlation is a similar measure to the commonly used Person's correlation but investigates ranked time series and is less subject to normally distributed data. In more detail, correlation is used in step 1: the verification for the member individual verification (~~chapter~~ section 4.1), in step 2: the skill analysis (~~chapter~~ section 4.2) for the factor individual forecast skill and in step 3: relevance (~~chapter~~ section 4.3) for the storm forecast skill for different data samples. Correlations are a straightforward statistic to use for either ~~relationships~~ relationship between two time series or even forecast skill (e.g., Befort et al., 2019; Athanasiadis et al., 2014; Scaife et al., 2014). Kendall correlation is used because it cannot be assumed that the data are normally distributed. ~~As this study builds up on Degenhardt et al. (2022), the~~ The same correlation method is used as in Degenhardt et al. (2022) for a better comparison, as this study builds upon their results.

4 Results

In the results ~~chapter~~ section, the focus will be on ~~those~~ 4 factors~~(2 primary and secondary factors respectively), which highlight~~. All investigation steps for all tested factors have been interpreted by the author and 4 factors highlighted the postulated link to forecast skill of winter storms clearly and best, MSLP Gradient, SST, Θ_e (850hPa), EGR (400hPa). More factors (see Table ~~1~~A1) have been tested within the ~~3-step-approach but not for~~ 3-step approach, but not all the required links could be clearly identified. Reasons may vary from factor to factor and will be discussed in the discussion section (~~chapter~~ section 5). Additional results for five moderate performing factors can be ~~find~~ found in the supplementary material (appendix Fig. ~~A2-A5~~A3-A6), EGR (700hPa), MSLP Meridional Gradient, Precipitation, Divergence (200hPa) & PV (350K).

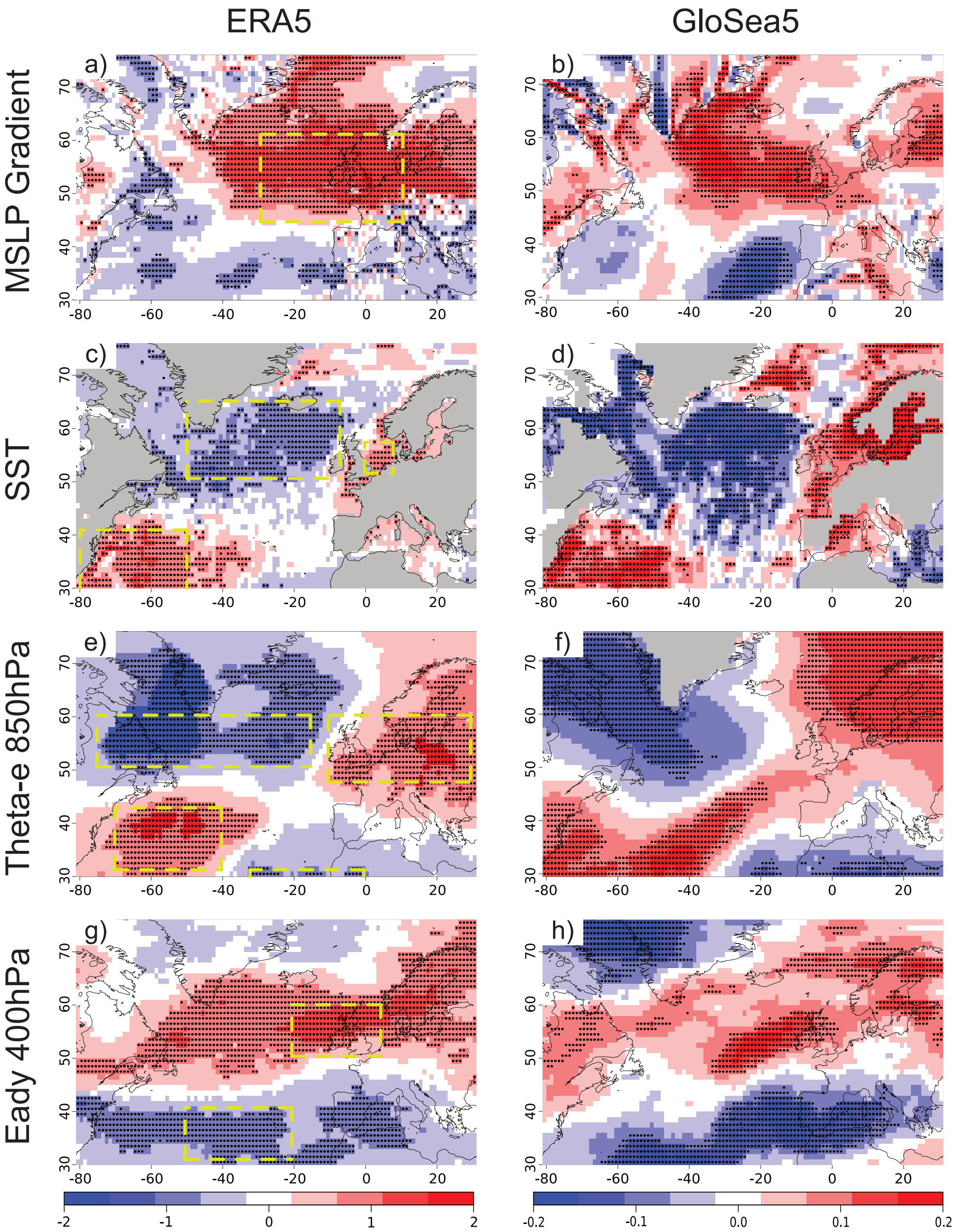

Figure 1. ~~Standardised~~ Composite Anomalies, standardised on climatology, of ~~factors~~ the respective factor for strong ~~vs.~~ storm seasons minus weak storm seasons in ERA5 (left column) and GloSea5 mean over all ensemble members (right column): a)&b) MSLP Gradient, c)&d) SST, e)&f) Θ_e, g)&h) EGR; dots shown for differences significant at the 90% level (p=0.9). Yellow boxes are selected regions for investigation step 3, Fig. 4, process-based-view (right column).

4.1 Validation of dynamical factors in GloSea5 via anomaly composite analysis - Does the model represent the same physical connections between causal factors as the reanalysis?

~~Is the physical connection between a causal factor and storm represented in the model as derived from reanalyses?~~ Composite anomalies of the dynamical factors separated into strong and weak storm seasons in the observational and model data are compared. Standardised composite anomalies for ERA5 and GloSea5 (mean over each ensemble member composite) are used to validate the individual factors on their connection to windstorms in both data sets (Fig. ~~3~~1; for 4 selected factors discussed in more detail here). The composite anomalies between strong and weak storm seasons give a useful indication of how the factors are connected to windstorms.

~~For the MSLP-Gradient, it~~ It is clearly identified for the MSLP-Gradient that a stronger storm season is characterised by a stronger MSLP-Gradient over the northern part of the North Atlantic, as expected. This pattern is coherent in observations and the model. The SST-pattern (Fig. ~~3~~1c & d) shows a clear tripole (positive-negative-positive anomaly) structure over the North Atlantic in ERA5 as well as in GloSea5 (Fig. ~~3~~1d). The GloSea5 mean signal (mean ~~over all~~ overall ensemble mean composites) is ~~less strong~~ weaker but still reveals a similar pattern. The three centres of action in the SST composite of ERA5 are ~~reflected as well~~ also reflected in the composite pattern of Θ_e. The model ~~mean of composites results~~ means of composites result in a quadrupole pattern for Θ_e but with a stronger influence of potential latent heat release over the centre of the North Atlantic than in ERA5. Also, EGR (400hPa) shows a clear and significant pattern over the North Atlantic, with higher baroclinicity in a latitudinal band around 50° N during strong storm seasons over the UK. ~~The secondary~~ These factors are known to have a link with cyclones and windstorms, but the former also ~~get~~ gets influenced by the latter. Nonetheless, the ~~influence of the~~ investigated windstorm systems (max. 2% of days per grid cell) will influence the seasonal average of the factors only marginally.

The appendix includes the composites for more factors (Fig. ~~A2~~A3) like EGR (700hPa), MSLP meridional gradient or PV (350K), which are showing in principle similar results as the previous factors, with a strong and coherent increase of the factor itself for stronger storm season over the UK in ERA5 and a good representation of a similar pattern in GloSea5. Nevertheless, precipitation ~~,~~ shows a north-south dipole in ERA5 downstream of the British Isles and Iberian Peninsula, which is less dominant in GloSea5, but also less relevant for windstorm forecasts. As Scaife et al. (2017b) suggest, tropical precipitation is ~~also~~ important for European forecast skill. The model has a strong signal and clear dipole around the equator, revealing ~~more~~ shifted precipitation in the tropics in strong ~~UK-storm~~ UK storm seasons.

Composites are categorical separations of data sets, which ~~is useful to clearly identify~~ are useful for identifying the difference between two data sub-samples ~~, but the time coherent~~ clearly. A time-coherent link between storms and factors is also of great interest~~, hence~~. Hence, a correlation analysis between the factors' time development (as time series) and windstorm frequency (as storm counts) is used for ~~validation~~additional validation (see Fig. 2). Maps are created to show the correlation link between the windstorm target region (the extended area of the British Isles) and systematic (10°x10° boxes over the whole North Atlantic) regions of the factor over the North Atlantic. Fig. ~~4~~ 2 presents the four focused factors as examples, with the remaining in the appendix (Fig. ~~A3~~A4).

These results show ~~in more detail~~ the regions where a factor is relevant ~~to~~ for windstorms over the extended area of the British Isles (red dotted box in each panel) and how this connection is represented in the different ensemble members (histograms). The results can be separated into two parts. First, only the ERA5 connection (1^{st} row of each box) compared to the GloSea5 member mean connection (2^{nd} row of each box). All factors show in each factor box the correlation ~~has~~ results in the same sign in ERA5 and GloSea5 member mean. Factor regions which are further outside of the storm-related area have some ~~discrepancy~~discrepancies, such as the MSLP gradient (Fig. ~~4~~2a) or PV (Fig. ~~A3~~A4e) region over ~~the Mediterranean~~Newfoundland or the eastern Mediterranean Sea. In these regions, GloSea5 members are not in ~~good~~ agreement with the observational relation. This can be seen in the second part of this figure's interpretation, the percentile of ERA5 within the GloSea5-member distribution. For example, the region around Newfoundland of the EGR (400hPa, Fig. ~~4~~2d) has a percentile for the ERA5-correlation in the GloSea5-member-distribution of 1, which means the significant correlation in ERA5 is far outside the GloSea5 member correlation distribution and hence statistically different. Another example, the SST box over the North Sea (Fig. 2b), has an ERA5-percentile of 0.56, so the GloSea5-member distribution covers the ERA5 correlation.

4.2 Skill of Factors - Is the dynamical factor skilfully predicted?

~~Is the dynamical factor skilfully predicted? After knowing~~ The previous results summarise that relevant factors are well represented in their physical connection to windstorms~~not only from~~. This had been shown for an ensemble mean perspective ~~,~~ (with composites, Fig. 1) but also within individual ensemble members ~~and thus representing~~ (correlations per member, Fig. 2). Thus, the GloSea5 model represents a consistent physical development ~~, the~~ between respective factors and windstorms with an agreeing spatial pattern, but weaker signals in the results. The next step tests if these factors themselves are well predicted. Thus, this step evaluates how far the model suite can forecast the necessary ingredients for storm development~~can be forecasted by the model suite. Thus, in those regions of important connections between factors and windstorms~~. The storm-relevant regions (section 4.1) ~~they~~ should be well predicted to ~~make an influence for~~ have a positive influence on the windstorm forecast performance. The Kendall correlation is used to assess the skill of the model's ensemble mean compared to ERA5. Fig. ~~??~~ 3 shows this correlation skill for the main four dynamical factors. MSLP-Gradient has a skilful and coherent region of predictability over the North Atlantic and the British Isles. The SST is ~~overall very well predicted~~ well predicted overall, with a small gap upstream of Newfoundland. The same gap but larger and stronger negative ~~correlated is identified as well~~ correlation is also identified for Θ_e. EGR (400hPa) correlates ~~significant~~ significantly in the region ~~downstream~~ upstream of the British Isles~~which is located north-east~~, northeast of the Atlantic storm track. Beyond the four main factor variables discussed thus far, EGR (700hPa) reveals the same area of skill as 400hPa (cf. appendix Fig. ~~A4~~A5). The MSLP meridional gradient shows an extended region of skilful forecasts over the North Atlantic compared to the total gradient ~~,~~but not the coherent skilful region over the British Isles. Precipitation, divergence and PV 350K ~~all~~ show very little to no skilful prediction close to the target region, the British Isles and Europe. However, precipitation is skilfully predicted in the tropics (cf. appendix Fig. ~~A4)~~A5), which is the region Scaife et al. (2017b) suggest to be important for European predictability, as this convective precipitation would trigger Rossby Waves which propagate towards the extra-tropics.

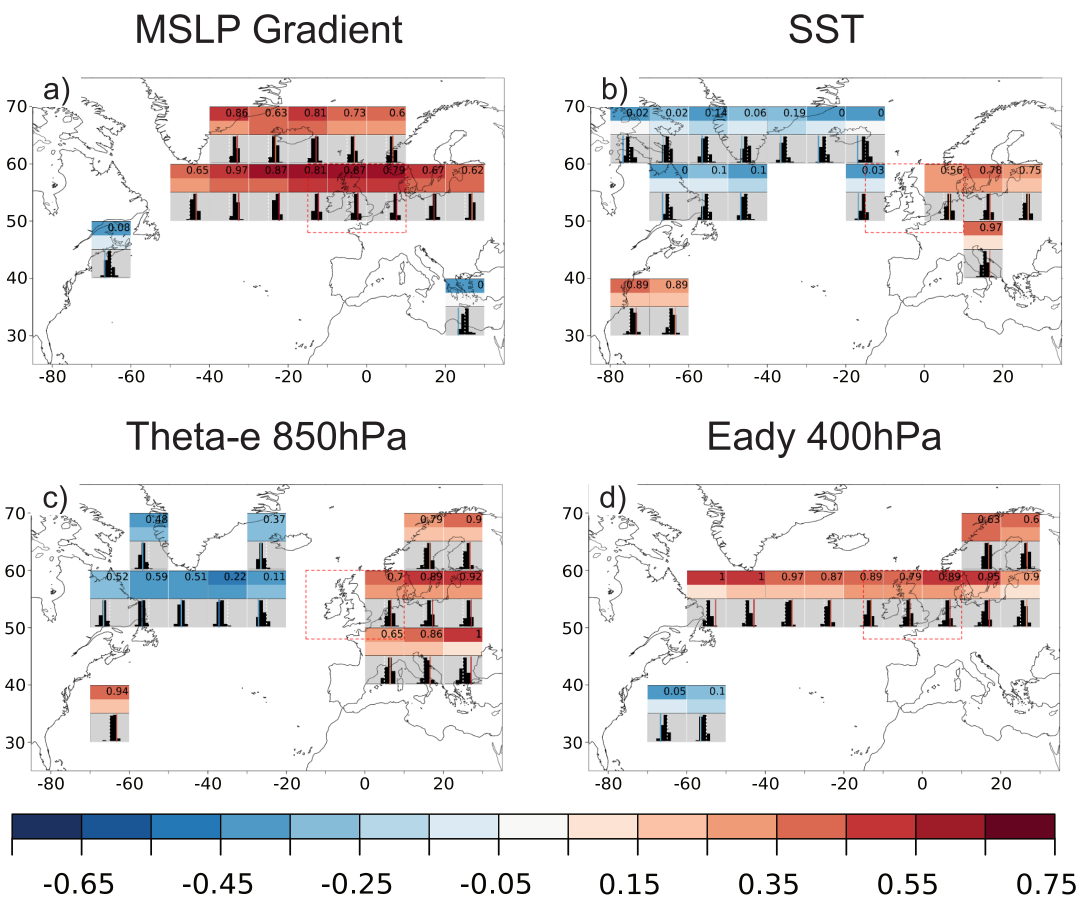

Figure 2. Correlation Maps between seasonal storm counts over the UK and dynamical factors (averaged in 10x10° regions). Only factors with a 95% significant ~~connections~~ correlation in ERA5 are shown. ERA5 connections (~~1st column~~1^{st} row), GloSea5 member connection mean (~~2nd column~~2^{nd} row), GloSea5 individual member ~~connection~~ correlation distribution (below). The distributions are scales from -1 to 1 with 0 in the centre. The coloured line is the ERA5 correlation value within the GloSea5 member distribution, and the number represents the percentile of ERA5 in that distribution.

4.3 Relevance of Factors for Storm forecast skill - Is the storm forecast skill (found by Degenhardt et al., 2022) related to the forecast skill of the factor or the regions that show a strong connection to windstorms?

~~Is the storm forecast skill (found by Degenhardt et al., 2022) related to the forecast skill of the factor or the regions that show strong connection to windstorms? To answer this final question, the previous results about factors have been related to windstorm forecast skill. The aim of this step is~~ The final step aims to find factors and individual regions influencing the seasonal forecast skill of windstorms. Therefore, the storm seasons data has been split into two sub-samples to generate two storm forecast skills depending on each sub-sample. These different characterised storms season sub-samples are separated by

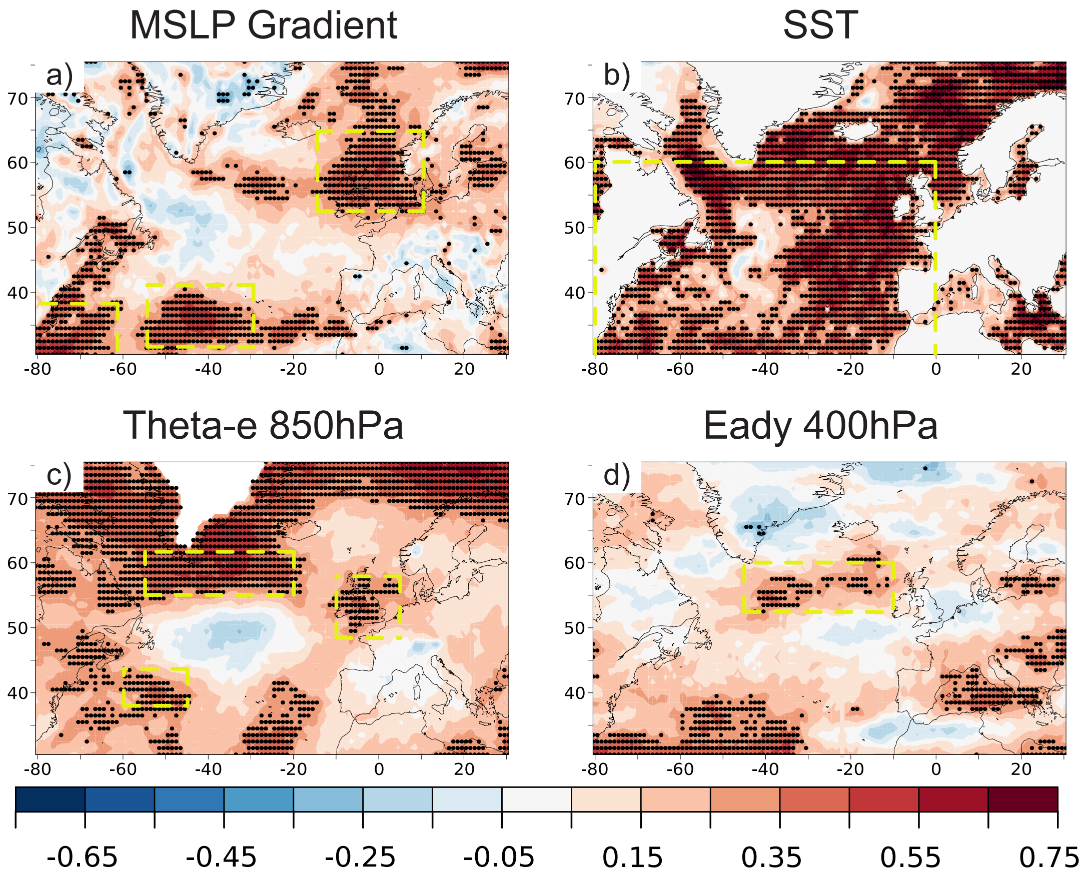

Figure 3. Kendall Correlation maps for selected dynamical factors between ERA5 and GloSea5 per grid cell, significance on 95% level marked by a dot. Yellow boxes are selected regions for investigation step 3, Fig. 4, (left column) factor-skill-view.

two approaches, one by the factor individual forecast skill (Factor-skill-view, results from ~~chapter~~ section 4.2) and one by the centre-of-action from the composite analysis (Process-based-view, results from ~~chapter~~ section 4.1).

In more detail:

a) The Factor-skill-view answers the question: "Does the existing factor's forecast skill improve the windstorm forecast?" Therefore, for the sub-samples of forecast skill, regions are selected that show ~~strong forecast skill~~ coherent regions of skilful forecasts for the individual factors, resulting from the approach-step-2: forecast skill (~~chapter~~ section 4.2, Fig. ~~??~~3). This first view ~~focusses~~ focuses on the regions with already existing and highest factor skill to assess whether the existing positive factor forecast skill in these regions is a source of the existing model's windstorm forecast and a potential improvement. If this is the case, it would mean that the correct ~~prediction of the factor~~ factor prediction leads to higher storm forecast skill. Thus, the storm seasons are split between well and bad predicted factor seasons.

b) The Process-based-view focuses on the question: “Does ~~areas of strong connection between factor and storm would~~ an improved factor forecast in areas of a strong connection (centre of action) improve the windstorm forecast?” This second view ~~is using regions~~ uses the same method as the factor-skill-view, but with other selected regions to create the sub-samples. The regions for this view are the ones that appeared most relevant in the connection between factor and windstorms (centre of action – ~~chapter~~ section 4.1, Fig. ~~3)to create the sub-samples for the different windstorm forecast skills. The aim of this view is to assess if~~ 1). This view aims to assess whether a better prediction of ~~these~~ the factors in these storm-relevant regions (”centres of activity”) would improve the seasonal windstorm forecast skill. ~~For this, the difference in storm forecast skill (based on correlations) is calculated between sub-samples created by well and bad predicted factorsseasons in the “centre of action”-regions~~These regions have not necessarily been selected because they are skilfully predicted in GloSea5 but because they show a physical link between storms and factors.

Fig. ~~?? shows differences of~~ 4 shows differences in the storm skill separated by both approaches, based on successful/bad predictions (factor-skill-view) and ~~on~~ the process-based view, respectively. The region used for separation is marked individually in each panel, some boxes might be out of the mapping area, but all ~~box-details~~ box details can be found in the appendix (Tab. ~~A1 & A2~~ A2 & A3). For both views, the selected regions (which can be multiple) are spatially averaged, and well- and bad-predicted seasons are detected by the absolute difference between the resulting ERA5- and GloSea5-time series in the used regions. The regions selected are those in which the respective factor is skillfully predicted. For the process-based view, this is not a criterion.

For factor MSLP Gradient, three boxes were identified from the factor forecast skill analysis (cf. Fig. ~~??~~3a) and this correlation difference in Fig. ~~??~~4a shows the storm forecast skill for years which are overall well predicted minus storm forecast skill of bad predicted years. It can be concluded that for years in which the MSLP Gradient in these three regions is well predicted, these years show an increase in storm prediction skill over parts of the North Atlantic, British Isles and Scandinavia. ~~In the~~ The second view, separated by centres of action in the composite anomalies (Fig. ~~3~~1a), shows a less strong increase in storm forecast skill for the selected region of MSLP Gradient ~~,~~ but still a slight increase in skill over Scandinavia. This shows the difference between the 2 separations. The process-based view (centre of action) improves the windstorm forecast skill less, and the regions ~~that are already skillful~~ already skilful in the factor forecast have more influence on the windstorm forecast skill. As SST was overall well predicted (Fig. ~~??b)~~3b), the whole North Atlantic region was used to identify well and ~~bad~~ badly predicted SST-seasons. When SSTs over the North Atlantic are well predicted, the total storm prediction skill over Europe increases. The Northern European part shows the ~~well predicted~~ well-predicted years have a significant value on these grid cells, but the bad predicted not (indicated by the dotes). The process-based-view for SST uses the four centres of action defined from the ~~composite-analysis~~ composite analysis (Fig. ~~3~~1c) in the North Atlantic. A good forecast in these four centres of action ~~lead to~~ implies an increase in windstorm forecast skill over Europe as well. The Θ_e relevance for windstorms is tested by using three regions of skilful Θ_e-forecast (Fig. ~~??~~3c). When all these three regions are well predicted, the windstorm forecast over Europe, especially Scandinavia and ~~East-Europe~~ East Europe, is increasing (Fig. ~~??~~4e). This means that the model ~~needs a well predicted~~ with a well-predicted Θ_e-value in these three Θ_e-poles ~~to~~ will create a skilful or even improved windstorms forecast. As Θ_e and SST seem to have a similar link to windstorms (composite patterns in Fig. ~~3~~1), as potentially higher SSTs

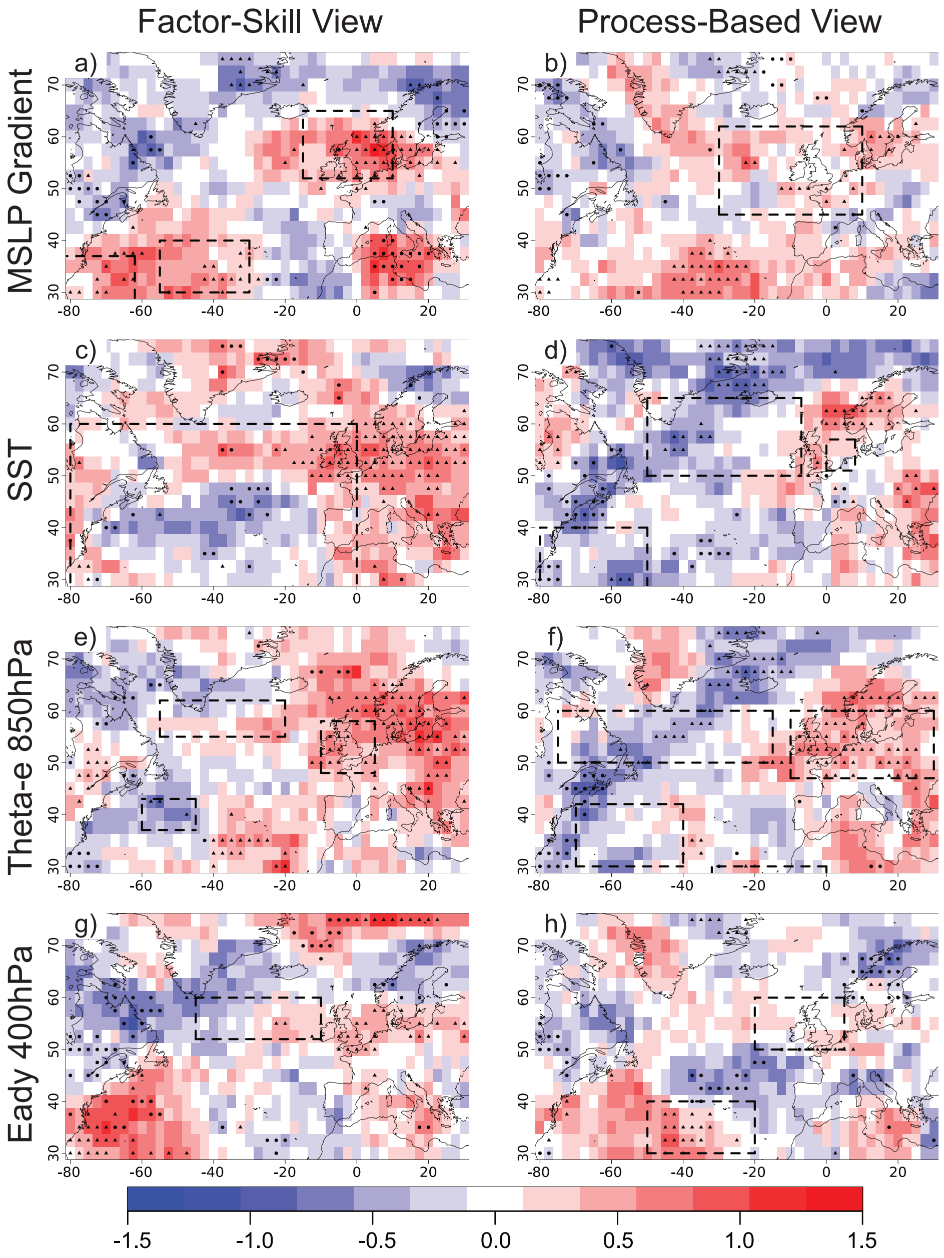

Figure 4. Difference of windstorm forecast skill (as Kendall correlation ~~difference~~ between ERA5 and GloSea5 windstorm ~~correlation for~~ frequency) with seasonal separation by the Factor-skill-view (left column) ~~well-bad predicted factor forecast seasons~~ and the Process-based-view (right column)~~centre of actions in composite anomalies~~. The separation is ~~made by~~ based on spatial averages over the shown ~~box~~ boxes from Fig. 3 for the left column and Fig. 1 for the right column, individually per factor. ~~Dot –~~Dotted grid cells showed significant storm forecast skill in the bad predicted season~~was significant~~, Triangle ~~–~~in the well predicted ~~season was significant~~sub-sample.

result in more convection, hence, more moisture in 850hPa and a higher Θ_e, these factors show very similar centres of action and the Θ_e process-based-view has similar four boxes selected as for SST. A good forecast of Θ_e in these four boxes ~~lead to~~ implies an overall increase ~~of~~ in seasonal windstorm forecast over Europe. This increase is higher and covers a bigger area than the increase by well-predicted SST regions, which might be because Θ_e ~~is a primary factor, hence, influencing~~ influences cyclonic systems directly, and SST is ~~a secondary factor which is more an atmospheric~~ more a global state surrounding the cyclonic systems. The relevant signal from the factor-skill-view is not as strong for EGR in 400hPa (Fig. ~~??~~4g,h) as for the previous three factors in the ~~same view~~respective views, but still is a ~~well predicted~~ well-predicted region related to an increase of storm forecast skill downstream the box and over the British Isles. As well as the factor-skill-view, the process-based-view ~~show~~ shows less increase in windstorm forecast skill for EGR compared to the previous three factors in this view. The remaining factors can be found in Fig. ~~A5~~A6, appendix. EGR in the lower troposphere (700hPa) has two very similar boxes in both views and hence, almost the same increase in windstorm forecast skill over Europe. Factors like MSLP meridional Gradient, precipitation and divergence show the skill-dependent selected regions are increasing the windstorm forecast skill over Europe significantly. The process-based-view is showing increasing signals for factors like precipitation and PV 350K.

5 Discussion and Conclusion

This study investigates the connection between ~~primary and secondary~~ atmospheric dynamical factors and the forecast performance of seasonal winter windstorm predictions. As skilful seasonal prediction for tracked windstorms ~~(Befort et al., 2019; Degenhardt et a~~ (Befort et al., 2019; Degenhardt et al., 2022; Lockwood et al., 2023) was recently shown, ~~the aim of this study was to further~~ this study aimed to explain the forecast skill further. A dependency of windstorms and ~~windstorm~~ their forecast skill on large-scale patterns, like NAO, SCA or EA, has previously been established (Degenhardt et al., 2022). Here, a more in-depth analysis of the mechanics of forecast skill generation is presented~~and consequently ,~~, and consequently, 10 ~~dynamical~~ dynamically important factors were selected and tested in multiple settings ~~with respect to~~ concerning their impact on the seasonal forecast skill of windstorm frequency (see Tab. ~~1~~A1). To reflect on the main contribution of those individual processes to the complex development of extra-tropical cyclones and storms, it has been differentiated between ~~primary (~~small-~~and~~ /short-scale ~~)~~ ~~or secondary (~~or large-~~and~~ /long-scale ~~)~~ factors. These factors are investigated in a 3-step approach: first, validation of the relevance of the factor to winter windstorms. Second, the forecast skill of the individual factor itself on a seasonal scale. And third, the relevance of the factor's forecast for the overall winter windstorm frequency forecast skill.

The strong link between windstorms and factors seen in the ERA5 composite anomalies of the four focus factors, MSLP gradient, SST, Θ_e and EGR (400hPa), are important because these four factors are knowingly the most driving factors for storm and cyclones (e.g., Pinto et al., 2008). The relation to windstorms for all these important factors is well simulated in the seasonal forecast suite, GloSea5. The SST shows the known horseshoe anomaly pattern (Nie et al., 2019a) and a clear connection is identified with a positive SST and Θ_e signal over Europe (Northern Sea and Baltic Sea): leading to stronger storm seasons as stronger SSTs may enhance Θ_e, leading to more baroclinic instability e.g., in the lower troposphere in favour of baroclinic wave development and thus for windstorms. The lower tropospheric EGR (700hPa) agrees with this concept in

ERA5, as the stronger EGR (700hPa) reaches over the North Atlantic until central Europe but lacks in spatial dimension in GloSea5. The SST composites in GloSea5 show similar three ~~centre~~ centres of action (positive - east of America, negative – south of Iceland and positive – North Sea), but a more extended negative SST composite anomaly in GloSea5 further south over the North Atlantic is in line with the recently found SST bias south of Greenland in CMIP6 models causing a bias in cyclone tracks (Priestley et al., 2023). The Θ_e composite anomalies of GloSea5 show a slightly different pattern over the North Atlantic, with a more extended positive signal reaching from ~~south-west to north-east~~ southwest to northeast than in ERA5. This is in line with the results from the factor precipitation, where in GloSea5, the North Atlantic precipitation is simulated further west. Studies like Fink et al. (2009) and Pinto et al. (2008) investigated storms from a Lagrangian perspective, but some of their characteristics can also be seen in the here presented Eulerian view. E.g., the dry pole in the ~~north-west~~ northwest of the Atlantic is in line with studies like Fink et al. (2009), which show the general atmospheric state around an extreme cyclone and that a strong cyclone leaves dry air behind. The composites of EGR (400hPa) in ERA5 and GloSea5 show a strong link of EGR just ~~downstream~~ upstream of the target area (extended region of British Isles). Especially the pattern of GloSea5 is in line with the knowledge ~~,~~ that EGR affects strong cyclones in a west-east band through their centre (Pinto et al., 2008) and the cyclone centre is located north of the windstorm field (cf. Leckebusch et al., 2008), which explains the strong EGR influence north of the North Atlantic windstorm track.

~~With mostly agreeing physical connection~~ The physical connections between windstorms and individual factors within the ~~observational and model data these~~ model data mostly agree with the connections in the observational data, especially on a spacial comparison. These connections may enhance model forecast ~~performance~~ performances when the individual factors are well ~~forecast themselves~~forecasted in the storm-relevant regions. The individual forecast skills of these factors show high and significant skill in ~~windstorm relevant~~ windstorm-relevant regions over the North Atlantic but also some gaps. The forecast skill of the upper tropospheric EGR is significant at the north-easterly end of the Atlantic storm track, ~~which is~~ an important area for ~~intensify~~ intensifying strong cyclones before making landfall in Europe. Even the forecast skill of the MSLP gradient, SST and Θ_e show significant skill around the British Isles, but the area around 50° N and 40° to 50° W is a gap for these factors. This reduction in forecast skill may link to previous studies, e.g. ~~Scaife et al. (2011)~~ Scaife et al. (2011); Athanasiadis et al. (2022), which identify large SST biases in model data.

After the factors have been verified ~~of~~ as having the same physical link in observations and models and the model shows forecast skill for important regions of the factor, the third step is connecting the factor performance to windstorm forecast skill. ~~For~~ It has been found that all main factors ~~it is found that increased~~ increase the forecast skill of winter windstorms over the British Isles and the North Sea by increasing the forecast skill of relevant factors in ~~relevant regionsis increasing the forecast skill of winter windstorms over the British Isles~~storm-relevant regions. SST and Θ_e additionally improve the windstorm forecast skill over Central Europe and Southern Scandinavia. The process-based-view, sub-sampling based on the centre of action from the composite analysis (step 1), is less conclusive~~, but especially for~~. But the factors SST and Θ_e ~~the~~ present four centres of action ~~help increasing~~ helping to increase the windstorm prediction over Europe when these regions are well predicted.

The overall conclusion from this three-step approach leads to a well-represented connection between the four focused ~~physical~~ dynamical factors and winter windstorm forecast skill. All four factors (MSLP gradient, SST, Θ_e & EGR 400hPa) show an agreement in the physical link, as composite analysis and in the stricter ~~correlation-maps~~correlation maps, suggesting the model does include the physical link overall correctly. ~~For all four factors the~~ The model provides positive forecast skill within relevant regions ~~,~~ for all four factors, which means the model performance for the individual factor is positive~~and well predicted seasons in these regions , supporting~~ . The final investigation step shows that well-predicted seasons of the factors in the relevant regions support skilful windstorm forecasts.

In addition, the further investigated factors (cf. appendix) show similar results. ~~Well predicted~~ Well-predicted regions of precipitation and divergence over the tropics and sub-tropics ~~are having~~ have a positive influence on ~~the~~ storm predictability over Europe. For precipitation, this is in line with Scaife et al. (2017b), ~~which~~ who found that tropical Atlantic precipitation ~~as~~ is an influencing factor for European predictability of atmospheric patterns. Further crucial factors (not shown) in this study were, e.g., the Rossby Wave Source (RWS), SST gradient (total and meridional component) or the North-America/North-Atlantic temperature gradient identified by Wild et al. (2015). ~~For the factor RWS no~~ The RWS factor did not show a clear pattern or relation~~was identified~~. The ERA5 composite is very scattered, but the GloSea5 mean shows at least a pattern agreeing with the conceptional idea of the tropical North Atlantic precipitation triggering convective rising, which triggers the RWS further North (Scaife et al., 2017b). A similar scattered result is ~~resulting for~~ seen from all approach steps for the SST gradients. The temperature dipole from Wild et al. (2015) has been tested, as a connection between North American surface temperature and North Atlantic sea surface temperature anomalies are linked to windstorms over Europe. But the results in this study are not conclusive, probably because the storm target region ~~is different~~ differs in both studies.

This study concludes that the existing windstorm forecast skill in GloSea5 can be explained by different dynamical atmospheric factors ~~which are primarily or secondary~~ connected to cyclones and windstorms. Thus, the model ~~is predicting~~ predicts the winter storm season well for the correct reasons, increasing ~~confidence in forecasts. Secondary and large-scale~~ forecast confidence. Large-scale factors like the MSLP gradient or SST ~~have a strong relation~~ strongly relate to windstorms in the observational and model data sets. Their ~~individual~~ seasonal forecast skill is high in storm relevant regions, and seasons which are well predicted have a positive influence on windstorm forecasts. The same is found for ~~primary~~ factors like Θ_e in 850hPa and EGR in the upper (400hPa) troposphere. This approach results in a new understanding of dynamical factors and covers multiple perspectives, which ~~give new knowledge where the windstorms~~ implies new knowledge about where the windstorm forecast skill might originate~~and where additional efforts, beside the also for windstorms existing signal-to-noise paradox (Degenhardt et al., 2022), are~~ . This also reveals areas for additional efforts needed to potentially improve windstorm forecast skill over the downstream end of the North-Atlantic storm track, alongside the also for windstorms existing signal-to-noise paradox (Degenhardt et al., 2022).

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Appendix A

This part of the Appendix ~~include~~ includes additional information about the method and calculation for the dynamical factors, hence for ~~chapter~~ section 3.2.

MSLP and SST represent more general information about ~~the~~ environmental conditions. Their respective gradients are calculated using the NCL (NCAR Command Language) implemented function (grad_latlon_cfd) and ~~compute~~ computed the absolute value of the gradient vectors. The Climate Data Operator (CDO; Schulzweida, 2019) has an implemented function (uv2dv) to calculate the respective wind divergence from both wind components (u & v)~~the respective wind divergence. For the calculation of~~. For calculating the Rossby Wave Source (RWS), the python package windspharm (Dawson, 2016) was used as an example script from GitHub. This script is based on the RWS equation used, e.g., by Beverley et al. (2019); Dunstone et al. (2018). Studies like Parker et al. (2019) investigated the jet stream on its seasonal predictability and connection to the NAO. This study follows their calculation of jet location and speed but for 200hPa rather than 850hPa. The jet is defined over a 9-day running mean of the zonal average of the wind~~,~~; both only the u-component ~~or~~ and the total wind ~~was~~ were tested. The jet location is defined here as the latitude at which the maximum wind (respectively u or total wind) is found, and as jet speed, the respective wind is used. An investigation from Wild et al. (2015) analysed how temperature anomalies over North America and the North Atlantic can influence the winter windstorm season over Europe. They created a Temperature-Dipole index which uses surface temperature at ~~2~~ two regions, one over North America (105° - 80° W, 38° - 55° N) and one over the western North Atlantic (85° - 50° W, 15° - 35° N). The difference ~~of~~ in the respective anomalies creates the so-called temperature index. The PV (Hoskins, 2015; Hoskins et al., 1985) is calculated using two implemented NCL-functions (pot_vort_isobaric

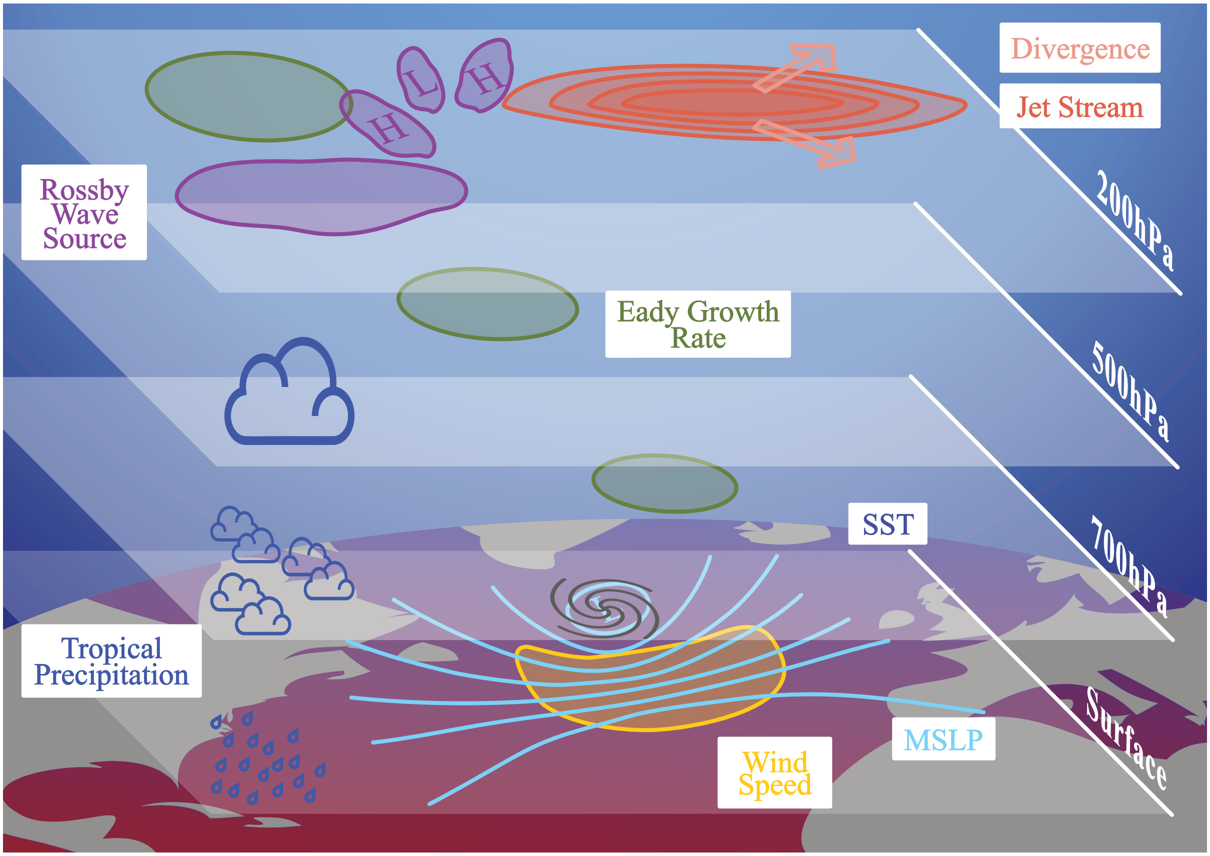

Figure A1. Schematic map of the spatial location of factors compared to an idealised storm system.

& int2p_n_Wrap). Therefore first, the pressure level data are used to calculate PV on pressure levels~~and secondly~~, and second, these values are interpolated onto ~~Θ-levels. The 350K-level~~ *Theta* levels. The 350K level is later used in this study. The PV Advection is calculated from the pressure-level data and then advected by both (u & v) wind components. Θ_e as an individual factor on 850hPa (Chang et al., 1984), is calculated with the NCL-function, pot_temp_equiv. The Eady Growth Rate (EGR) is calculated with an implemented NCL function (eady_growth_rate) which uses the 2-layer approach. This means whenever it is referred to EGR at 400hPa, it is calculated ~~by~~ using data from 300hPa and 500hPa, and for EGR at $\sim$700hPa, it is 500 & 850hPa. ~~Both,~~ PV and EGR are additionally analysed in this study after ~~an additional~~ post-processing ~~,~~ with a bandpass filter. This bandpass filter was run with an ~~R implemented~~ R-implemented function using the Butterworth filter (Butterworth, 1930), with ~~a~~ filter characteristics of 2 to 8 days for PV and 2 to 4 days for EGR. The filter was performed for each GloSea5 member individually. Because of data storage and computational times, the filtering was only executed for a region -100° to 40° E and 30° to 75° N. The total precipitation is used as in Scaife et al. (2017b) to investigate the link between tropical precipitation and the predictability of European climate conditions, like geopotential height. To be not restricted ~~on~~ to the four used tropical regions used in Scaife et al. (2017b) and for a better comparison to the other used factors, the seasonal precipitation mean is investigated on the grid-cell level.

This part of the Appendix includes the results for the remaining tested dynamical factors. Therefore, it belongs to the Result ~~chapter~~ section 4.

Table A1. Dynamical Factors (all tested for this study) concerning storminess, cyclones or windstorms over Europe.

Factor	Version	Level	Parameter (ERA5/GloSea5)	Analysis Regions
Temperature Dipole index		Surface	sea surface temperature (6h/6h)	North America (105°-80° W, 38°-55° N) North Atlantic (85°-50° W, 15°-35° N)
Sea-Surface Temperature	Original			Boxes of 10°x10° over North Atlantic
	Gradient			
	meridional Gradient			
Mean Sea-Level Pressure	Gradient		mean sea level pressure (6h/6h)	
	Meridional Gradient			
Total precipitation	mean		total precipitation (1h/daily)	
	Only December mean			
Jet	Location	200hPa	u- & v-wind component (6h/12h)	60°-0° W, 30°-75° N
	Speed			
Potential Vorticity	original	350K	u- & v-wind component, temperature T (6h/12h)	Boxes of 10°x10° over North Atlantic
	Bandpass 2-8d			
	Advection	400hPa		
Equivalent potential Temperature Θ_e		850hPa		
Eady Growth Rate	original	400hPa	u, T, Geopotential (6h/12h)	
	3d variability			

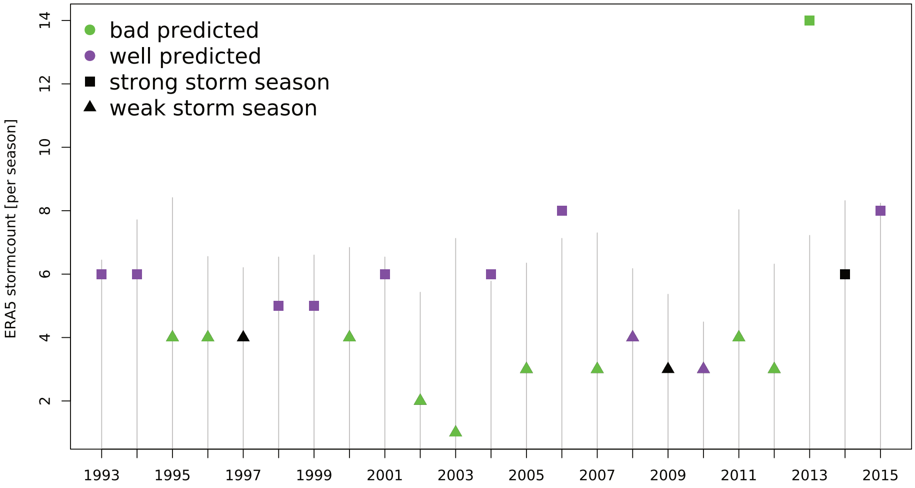

Figure A2. ERA5 UK storm counts as dots, and GloSea5 ensemble mean counts as bars. Bad predicted seasons (green), well predicted seasons (purple), weak ERA5 seasons (triangles) and strong ERA5 seasons (squares).

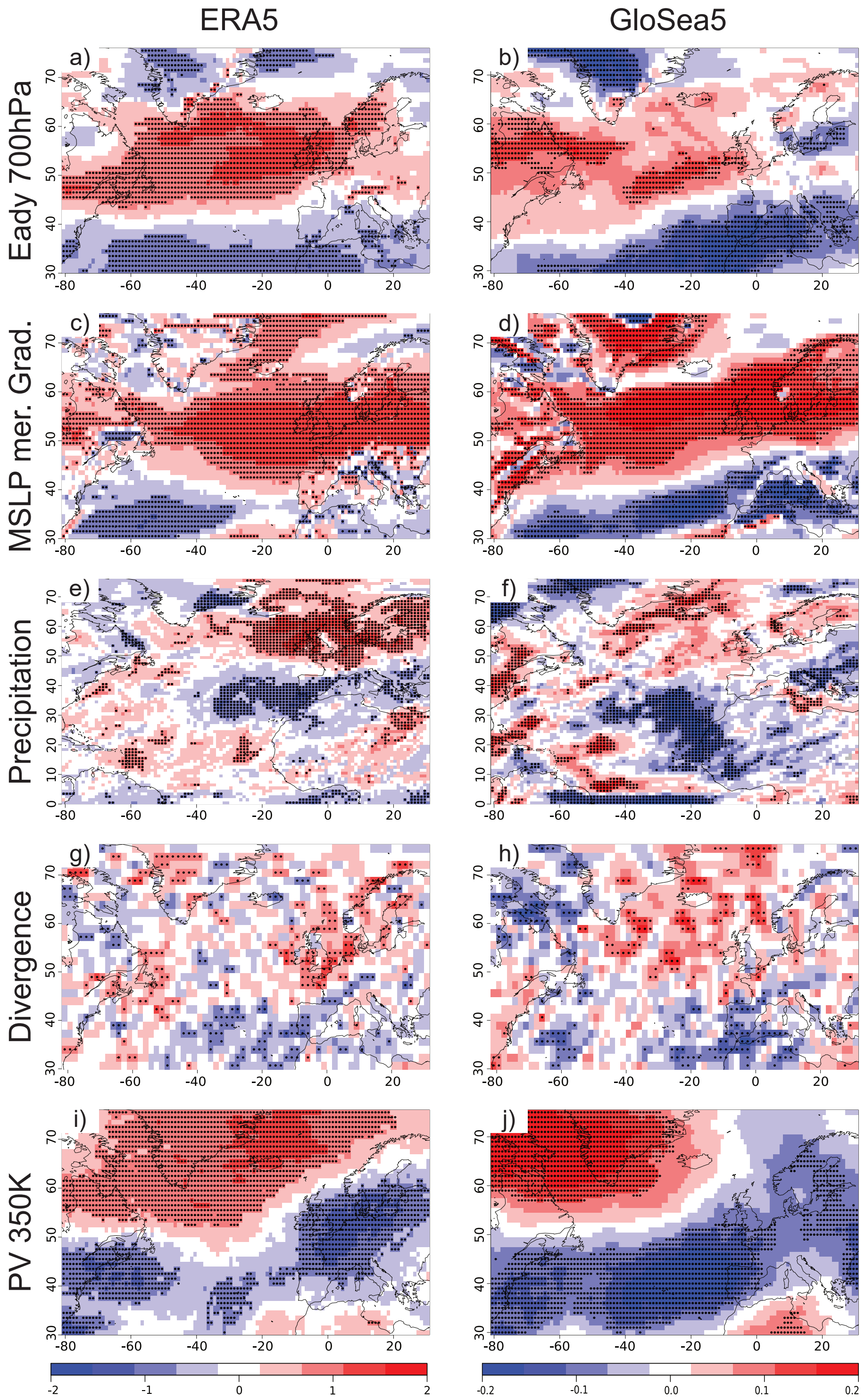

Figure A3. As Fig. ~~3~~ 1 for remaining ~~primary and secondary~~ factors.

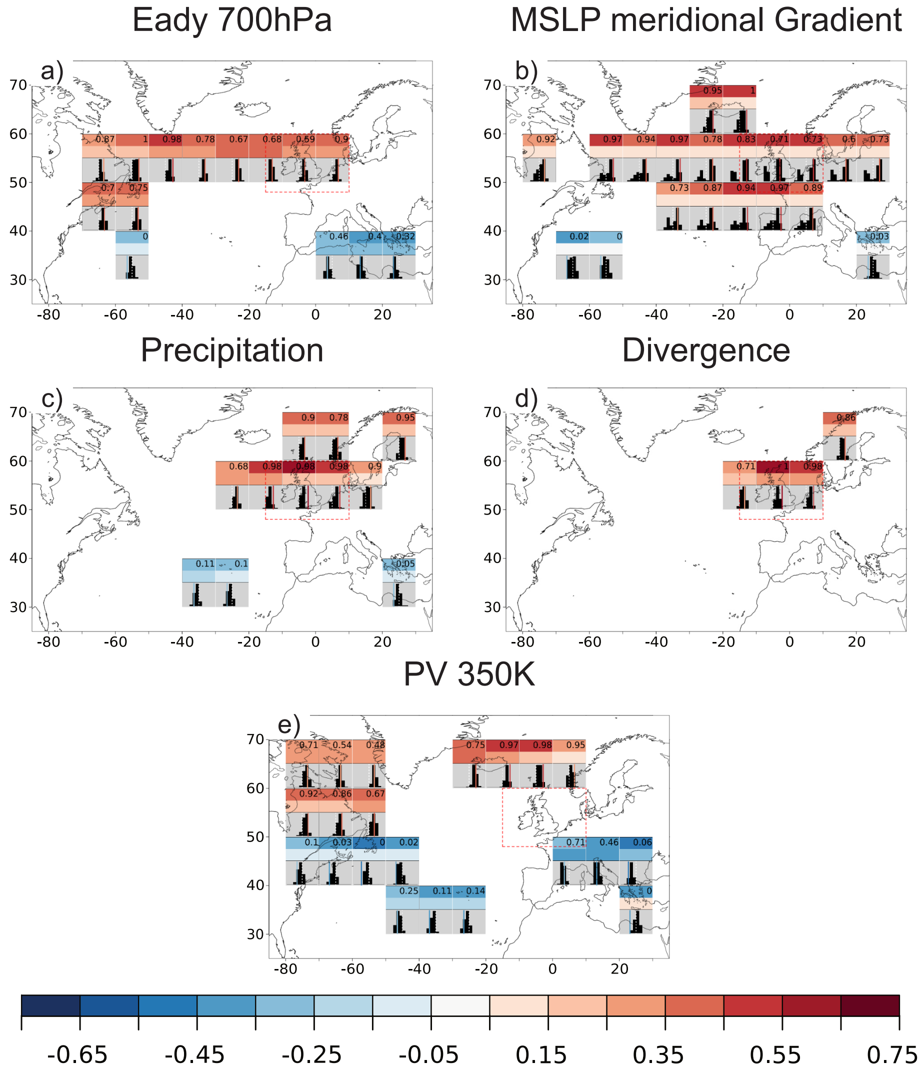

Figure A4. As Fig. ~~4~~ 2 for remaining ~~primary and secondary~~ factors.

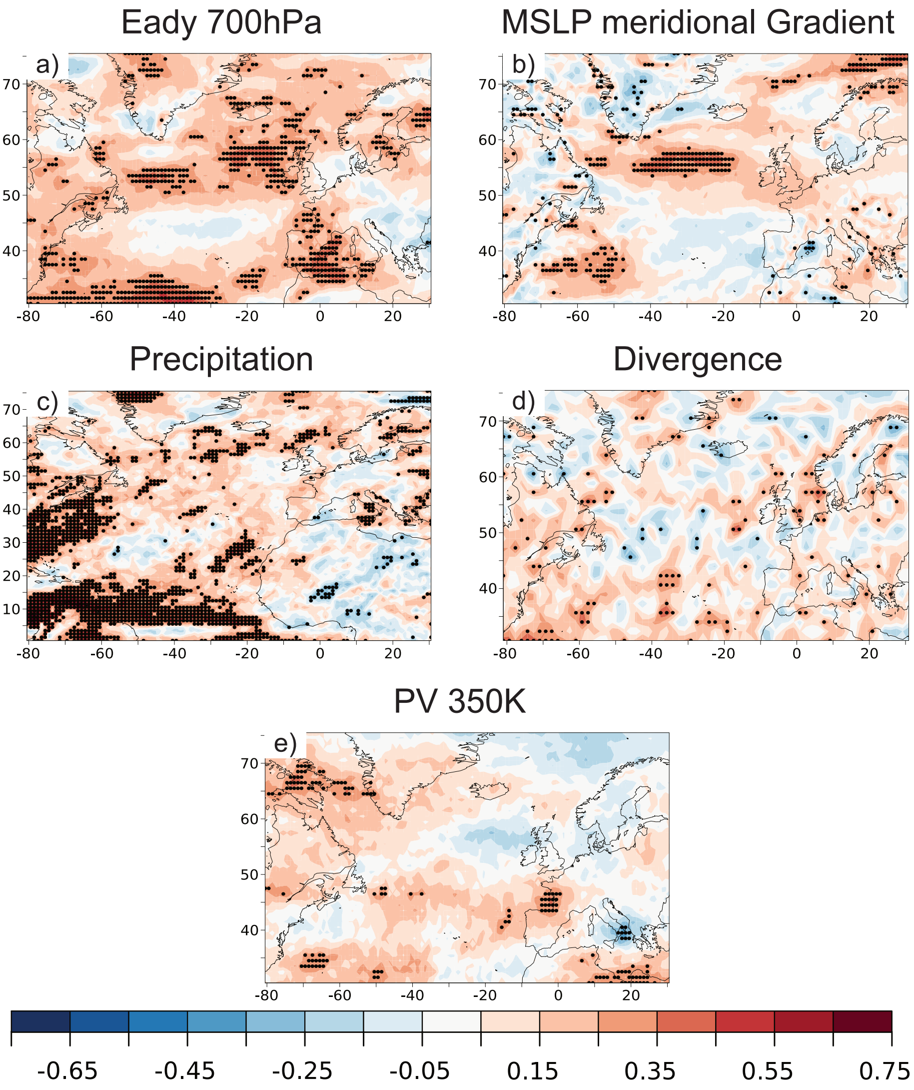

Figure A5. As Fig. ~~??~~ 3 for remaining ~~primary and secondary~~ factors.

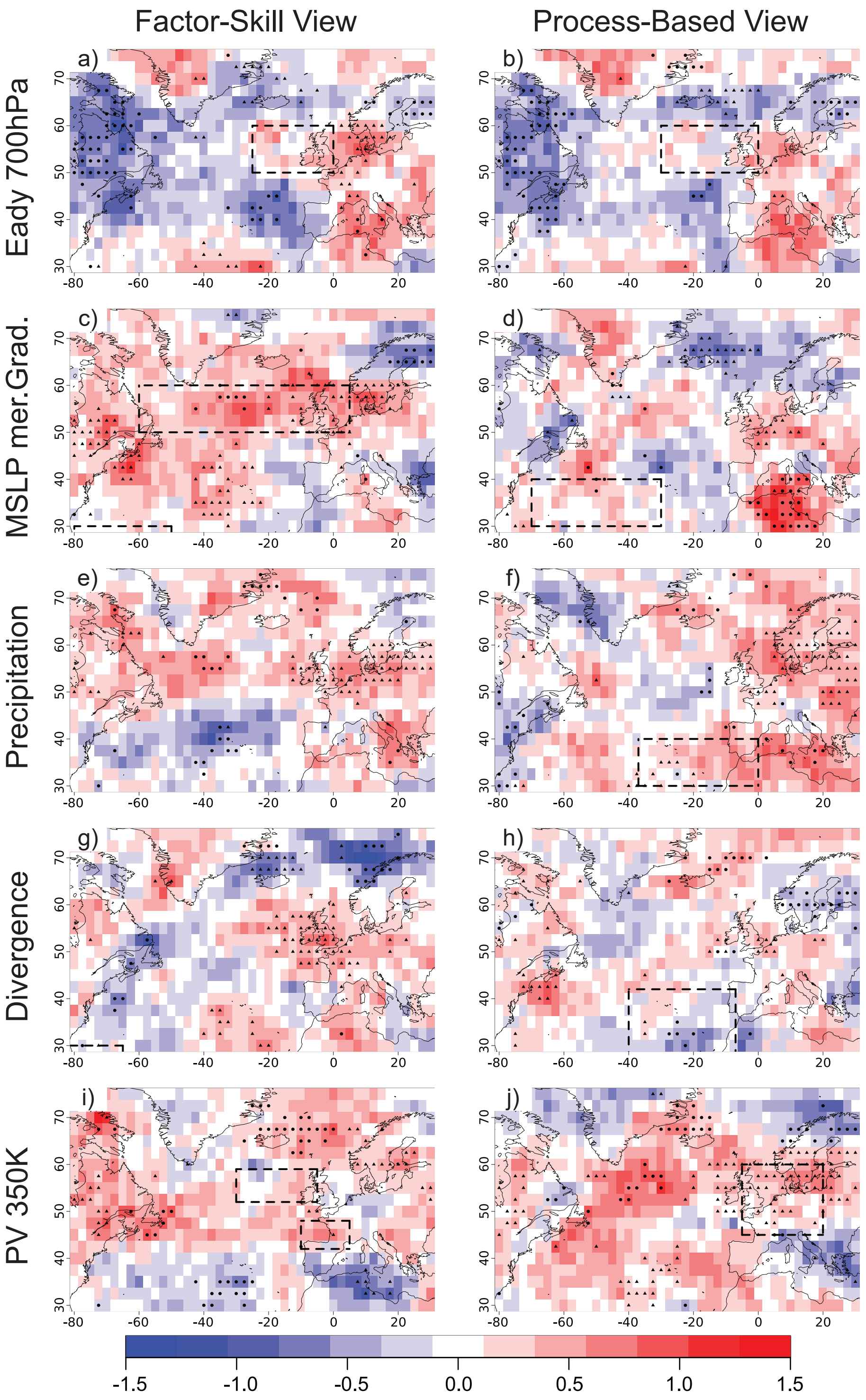

Figure A6. As Fig. ~~??~~ 4 for remaining ~~primary and secondary~~ factors.

Table A2. ~~Tested skilful~~ Skilful regions of factor forecast skill used for factor-skill view in Fig. 4.

Factor	Box 1	Box 2	Box 3	Boxmean
Mean Sea-Level Pressure Gradient	-15° - 10° E 52° - 65° N	-55° - -30° E 30° - 40° N	-85° - -62° E 27° - 37° N	Box 1-3
Sea-Surface Temperature	-35° - -5° E 40° - 64° N	-80° - -45° E 20° - 35° N	-80° - 0° E 10° - 60° N	Box 1&2
Equivalent Potential Temperature Θ_e	-10° - 5° E 48° - 58° N	-60° - -45° E 37° - 43° N	-55° - -20° E 55° - 62° N	Box 1-3
Eady Growth Rate 400hPa	-45° - -10° E 52° - 60° N			
Eady Growth Rate 700hPa	-25° - 0° E 50° - 60° N			
Mean Sea-Level Pressure Meridional Gradient	-60° - 5° E 50° - 60° N	-80° - -50° E 10° - 30° N		Box 1&2
Total Precipitation	-85° - -15° E 5° - 20° N	-90° - -55° E 20° - 45° N		Box 1&2
Divergence	-90° - -65° E 20° - 30° N			
Potential Vorticity 350K	-30° - -5° E 52° - 59° N	-10° - 5° E 42° - 48° N	-30° - -10° E 12° - 24° N	Box 1-3

Table A3. ~~Tested relevant~~ Relevant regions of ERA5 & GloSea5 ~~composite anomalies~~for the process-based view in Fig. 4.

Factor	Box 1	Box 2	Box 3	Box 4	Boxmean
Mean Sea-Level Pressure Gradient	-40° - 0° E 30° - 40° N	-30° - 10° E 45° - 62° N	-40° - 0° E 15° - 30° N		Box 1-3
Sea-Surface Temperature	-80° - -50° E 27° - 40° N	-50° - -7° E 50° - 65° N	0° - 8° E 51° - 57° N	-20° - -10° E 21° - 27° N	Box 1-4
Equivalent Potential Temperature Θ_e	-70° - -40° E 30° - 42° N	-32° - 0° E 25° - 30° N	-10° - 30° E 47° - 60° N	-75° - -15° E 50° - 60° N	Box 1-4
Eady Growth Rate 400hPa	-50° - -20° E 30° - 40° N	-20° - 5° E 50° - 60° N			Box 1&2
Eady Growth Rate 700hPa	-70° - 10° E 25° - 35° N	-30° - 0° E 50° - 60° N			Box 1&2
Mean Sea-Level Pressure Meridional Gradient	-70° - -30° E 30° - 40° N	-30° - 10° E 45° - 57° N	-40° - 0° E 15° - 30° N		Box 1-3
Total Precipitation	-37° - 0° E 30° - 40° N	-25° - 10° E 50° - 62° N			Box 1&2
Divergence	-40° - -7° E 42° - 27° N	-15° - 7° E 45° - 63° N			Box 1&2
Potential Vorticity 350K	-5° - 20° E 45° - 60° N	-80° - -52° E 15° - 23° N			Box 1&2